NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3334

FRICTION OF POSSIBLE SOLID LUBRICANTS WITH VARIOUS CRYSTAL STRUCTURES

By Marshall B. Peterson and Robert L. Johnson

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SUMMARY

A number of possible solid lubricants with various crystal structures were tested in a low-speed, high-load, friction apparatus under conditions of continuous sliding. Some solids with the $CdCl_2$, CdI_2, MoS_2, and other layer-lattice types provided effective lubrication. Those materials include CdI_2, $CdCl_2$, PbI_2, $CoCl_2$, $AgSO_4$, $CuBr_2$, and WS_2. They were not as effective as MoS_2 but were at least as effective as zinc stearate and graphite in these tests. Not all solids with these structures were good lubricants; the criterion for good lubrication over extended periods seemed to be the formation of a film on both mating specimens. Some low-shear-strength materials that did not have a layer-lattice structure afforded surface protection.

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INTRODUCTION

The use of solids as lubricants has become important in recent years because of the possibility for their use at high temperatures and at high loads. Graphite and MoS_2 have been used extensively. The lubricating capacity of these compounds has been attributed to their layer-lattice structure and, in the case of graphite, to adsorbed moisture or gases on the crystal surfaces. In the case of metallic salts with the general formula AX_2, this layered structure may be represented as

$$\begin{array}{cccc} X^- & X^- & X^- & X^- \\ A^{++} & A^{++} & A^{++} & A^{++} \\ X^- & X^- & X^- & X^- \\ \hline X^- & X^- & X^- & X^- \\ A^{++} & A^{++} & A^{++} & A^{++} \\ X^- & X^- & X^- & X^- \end{array}$$

where the forces within the layer are the strong covalent or ionic forces, while the forces between the successive layers are the relatively weak molecular or Van der Waals forces (ref. 1).

There are three general types of layer lattice in the case of the AX_2 compounds: the $CdCl_2$ type, the CdI_2 type, and the MoS_2 type. In the $CdCl_2$ and the CdI_2 type lattice, the forces within the layer are more ionic in character than they are with the MoS_2 type lattice; the difference between the $CdCl_2$ type and the CdI_2 type is in the position of one layer upon the other. Although only MoS_2 and WS_2 have the MoS_2 lattice type, there are numerous compounds that have the $CdCl_2$ and the CdI_2 type structure. A list of such AX_2 compounds formed by common divalent and quadrivalent cations and anions along with their crystal types is shown in table I (data taken from ref. 2). This table does not, however, represent a complete series, for it would be expected that substitution of other easily polarized anions would also result in a similar structure.

As a guide in the selection of possible solid lubricants, it is desirable to know whether layer-lattice structures such as $CdCl_2$, CdI_2, etc., also possess the lubricating properties of MoS_2. Research was therefore undertaken at the NACA Lewis laboratory to check the lubricating effectiveness of several layer-lattice solids and to further understand the basis of their lubricating action. A secondary purpose was to indicate whether or not a layer-lattice structure was sufficient as the primary criterion for a good solid lubricant. Therefore, a series of friction tests was run with several solids that did not have a layer-lattice structure.

A basis for interpreting the friction data reported herein can be obtained by considering variations in the amount of metal contact and differences in the shear strengths of the films in accordance with the following concepts: The coefficient of friction for unlubricated metals has been expressed as

$$\mu = \frac{\text{Area of shear} \times \text{shear strength}}{\text{Load}}$$

According to the theory of friction of Bowden and others (ref. 3), the ratio $\frac{\text{load}}{\text{area}}$ = constant = p = flow pressure of the softer of the two friction specimens (in these experiments, 1020 steel). When a thin film of lubricating material is placed between the surfaces, the load is supported by the base material and the pressure will be equal to the flow pressure of the softer material. However, the shear strength S will then be the shear strength of the lubricating film:

$$\mu = \frac{\text{Shear strength of film, S}}{\text{Flow pressure of softer specimen material, p}}$$

If some metal contact exists through the film, the coefficient of friction will be increased by an amount proportional to the amount of metal-to-metal contact. This increase may be represented thus:

$$\mu = \alpha \frac{S_{metal}}{p} + (1-\alpha) \frac{S_{film}}{p}$$

where α is the fraction of metal contact existing at any time.

The tests were run using a low-speed friction apparatus in which the solid was applied as a dry powder. Friction force and wear were measured under conditions of continuous sliding at room temperature.

APPARATUS AND PROCEDURE

Apparatus

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The apparatus shown in figure 1 is essentially the same as that described in reference 4 except for the slider specimen. In this investigation, three hemispherical sliders were rotated against a flat disk (fig. 2). The sliders were made of 1095 steel (Rockwell B-97) and were ground with a 3/16-inch radius. The disk (1020 steel, Rockwell A-50) was given a vapor-blast surface finish to avoid the directional nature of ground surfaces and to better maintain the lubricant film.

The sliders were mounted in a holder that was clamped in the jaws of a spindle. The spindle could be raised, lowered, or locked in any position. The disk was placed on a support table and kept from rotating by means of a pin on the support table which meshed with a hole in the edge of the disk. A ball bearing in the base of the apparatus allowed free movement and had a negligible effect on the total friction force. The friction force was measured by restraining the lower assembly through a dynamometer ring on which strain gages were mounted.

The support table rested on three springs, which compensated for minor misalinement of the sliders and disk. The load was applied by lowering the spindle and compressing the base springs. The magnitude of the load was indicated by the dial gage, which had previously been calibrated using dead weights.

Cleaning Procedure

Prior to each run, both the disk and the slider specimens were cleaned according to the following procedure:

(1) Washed in 50/50 acetone-benzene solution

(2) Scrubbed with repeated applications of moist levigated alumina

(3) Washed in tap water

(4) Washed in distilled water

(5) Washed in 95-percent alcohol

(6) Dried in a stream of warm air and stored in a desiccator

Preparation of Solids

The solids used in this investigation along with their purity and other chemical considerations are listed in table II. Those materials which were deliquesent or hygroscopic were heated to approximately 300° F for 1/2 hour prior to their use. Powders of $NiCl_2$ and $CoCl_2$ were obtained by heating their hydrates for 1 hour at 300° F.

Test Procedure

In reference 4 it is shown that humidity had a pronounced effect on lubrication with MoS_2. It was therefore considered important to eliminate humidity as an experimental variable. Consequently, the test specimens were surrounded by a jacket, and an atmosphere of dry air (<-60° F dew point) was maintained throughout the tests unless otherwise specified.

The cleaned test specimens were placed in the apparatus and dried in air of dew point <-60° F for 1/2 hour. Enough of the powdered solid was added (20 g) to cover the disk to a depth of about 1/4 inch. The powder was then dried for an additional 1/2 hour. A load of 40 pounds was applied and the friction force noted for continuous sliding for 1/2 hour. At the conclusion of the run, the amount of wear was determined with a planimeter by measuring areas of the wear spots from projected enlarged images of the wear areas on the slider specimens. At the end of each run, all specimens were examined microscopically and photographed.

RESULTS

The results are presented in three sections. The first section presents friction coefficient - time curves for common lubricants; the second section presents curves for typical layer-lattice structures, primarily the AX_2 compounds; the third, for several low-shear-strength materials that do not have layer-lattice structures. The data presented, except in those cases where complete failure resulted, are typical runs of at least two tests on the same material.

A summary of the results, including coefficients of friction after 1 minute of sliding and after 30 minutes of sliding as well as the area of the wear spot, is presented in table II.

Common Lubricants

Coefficients of friction ranging from 0.10 to 0.15 are most common in effective boundary lubrication with liquid lubricants. For purpose of discussion, coefficient of friction values below approximately 0.10 are referred to herein as low values. In general, surface failure or excessive metal contact and wear are reflected in increased or erratic coefficients of friction; however, there can be exceptions to this relation.

In order to compare the lubricating effectiveness of the solids used in this investigation with common lubricants, tests were conducted using graphite, MoS_2, zinc stearate, and SAE 60 oil. These data are shown in figure 3. The coefficient of friction for the SAE 60 oil was that expected for boundary lubrication. With MoS_2, the coefficient of friction was low and remained low throughout the tests. Photographs taken at the end of the MoS_2 run (fig. 4) show that a continuous film was maintained on the slider and on the disk. When graphite was run in dry air, complete friction failure accompanied by severe surface damage resulted; for this reason graphite was run in moist air. The coefficient of friction was initially low, then gradually increased to a stable value of 0.105. Zinc stearate showed a similar trend, except for the first friction value which was 0.12. Photographs of the slider and disk from graphite and zinc stearate runs are shown in figures 5 and 6, respectively. The final wear area along with the 1- and 30-minute values of friction are given in table II.

The increase in friction after 1 minute of sliding with zinc stearate and graphite was probably the result of an increase in the amount of metallic contact at the tips of the asperities. After 1 minute of sliding, the friction reading became more erratic, which was a good indication that metal contact took place; further, the photographs of the surfaces showed evidence of metal protrusions through the lubricant film. The friction coefficient was then rather stable at 0.10 because the lubricant that had collected in the interstices between the asperities on the disk and on the slider flowed and partially protected the surface.

Other solids have been found under certain conditions to afford adequate protection to sliding surfaces. Experimental evidence indicates that when formed as reaction films on metal surfaces Fe_3O_4 (ref. 5) and NiO (ref. 6) were effective in providing surface protection. Mica, talc, and boron nitride BN have been added to greases and oils to enhance lubrication. Experiments were performed to determine if those materials (Fe_3O_4, NiO, mica, talc, and BN), which others have found to supplement the functioning of conventional lubricants, would also be effective as dry powdered solid lubricants under the conditions of this investigation. For those materials, the friction force was characteristic of the unlubricated metal surfaces, the powders did not remain in the contact areas, and severe galling of the sliders and disks resulted. (Representative photographs, fig. 7.)

Layer-Lattice Structure

Solids with $CdCl_2$ type lattice. - Tests were run with three solids that had the $CdCl_2$ type lattice: $CoCl_2$, $NiCl_2$, and $CdCl_2$. The friction-time curves are shown in figure 8 and the wear areas in table II. The initial coefficients of friction were comparable to that obtained for MoS_2 but an increase was observed (as in the case of zinc stearate and graphite) after several minutes of sliding. The condition of the disk was also similar to that observed for the zinc stearate; namely, metal visible through the lubricant film at the tips of the asperities on the disk; however, with these compounds no film was observed on the slider. Thus the increase in friction after several minutes was probably the result of the increase in amount of metal contact. A typical photograph of the slider and disk ($CoCl_2$) is shown in figure 9.

Solids with CdI_2 type lattice. - Tests were also run with compounds that have the CdI_2 structure: $Mg(OH)_2$, TiS_2, PbI_2, $Ca(OH)_2$, and CdI_2. Solid iodine was included for comparison purposes. These data are shown in figure 10. The curves for PbI_2 and CdI_2 maintained a rather steady value for the 1/2-hour test. Another test with CdI_2 was run for 20 hours without any increase in the friction or the wear. The curves for I_2, $Mg(OH)_2$, TiS_2, and $Ca(OH)_2$ all show an increasing trend with time; examination of these specimens at the end of the test showed that there was no apparent film on the slider and that much metal was visible through the film on the disk (representative photograph for $Ca(OH)_2$ shown in fig. 11). However, with both CdI_2 and PbI_2, a continuous film was maintained on both the slider and the disk. A representative photograph for PbI_2 is shown in figure 12.

Solids with MoS_2 type lattice. - The friction-time curves for two solids with MoS_2 type structure, MoS_2 and WS_2, are shown in figure 13 and the wear areas in table II. The friction coefficient of WS_2 decreased initially and then increased to a steady value.

Other layer-lattice solids. - Tests were also run with several layer-lattice solids chosen from reference 2 that were not of the $CdCl_2$, CdI_2, or MoS_2 type structure. The friction-time curve for HgI_2 is shown in figure 14. The friction is rather high; however, a continuous film was observed on the slider and disk.

The friction values for $PbCl_2$ and $HgCl_2$ are high and erratic (fig. 14); the two curves represent the maximum and minimum values in a single run. An increasing trend in friction was also recorded.

The friction-time curve for $CuBr_2$ is also shown in figure 14. This structure consists of $CuBr_2$ chains arranged in such a way that a layer structure is produced (ref. 7). Low friction was maintained throughout the test and a continuous film was maintained on the slider and disk; this film, however, decomposed rapidly when exposed to moisture. This result indicates that other compounds with this chain structure may be effective solid lubricants. Because of its instability in the presence of moisture, $CuBr_2$ does not appear suitable.

Silver sulfate has been suggested as a possible solid lubricant (ref. 8). The friction curves for Ag_2SO_4 and isomorphous Na_2SO_4 are shown in figure 15. Although the friction for Ag_2SO_4 was relatively high in comparison with MoS_2, examination of the slider and the disk showed that Ag_2SO_4 had adhered to both (figs. 16(a) and (b)). When this film was dissolved away, very little surface damage to the slider or the disk was visible (figs. 16(c) and (d)). With Na_2SO_4, friction was initially high and erratic, followed by complete surface failure.

Low-Shear-Strength Solids Without Layer-Lattice Structure

Several compounds (AgCN, CuCl, and AgI) were tested which have low shear strength (ref. 9). These data are shown in figure 17. The compound AgCN, which has a very low shear strength, gave low initial values but after approximately 5 minutes of sliding, friction values became erratic and began to increase. Examination of the specimen after 15 minutes of sliding showed no film on the slider and part of the disk. This removal of the lubricating film would cause increased and erratic values of friction.

When CuCl was used as a lubricant, the friction decreased initially and then increased slightly; the friction values were rather erratic.

The friction-time curve for AgI increased from an initial value of 0.19 to a steady value of 0.25 after 5 minutes of sliding. The surfaces of the specimens when AgI was used as a solid lubricant (fig. 18) were similar to those that were found when using many of the layer-lattice structures as lubricants, namely, a continuous film on the slider and disk with the asperity tips visible through the film on the disk.

The ability of the solid to lubricate seemed to be associated with its ability to form a film on the surfaces. Those materials that did not form a film gave immediate surface failure; if a thick film was built up on both the slider and the disk, the friction force reflected the shear strength of the solid lubricant. The effect of sliding is to wear away this thick film and allow metal contact between the surfaces; the resulting friction force will then be a function of the shear strengths of the solid lubricant and the metal junctions as well as the ratios of the areas involved. The way these films are worn away from the slider and from the disk is reflected in the shape of the friction-time curves. For example, with Ag_2SO_4 a thick film was built up and maintained on the slider and disk, friction remained constant throughout the test. With PbI_2 or CdI_2, a film was initially present but was quickly worn thin so that some metal contact existed between the slider and the tips of the asperities. The friction force then increased to a rather stable value and remained constant; this was probably due to the fact that the residual material between the asperities could replenish the film on the slider and at the asperity tips.

Those materials that adequately protected the surfaces from galling and wear are considered most effective as possible solid lubricants. A low slope on the friction-sliding time curve for a given material was a dependable indication of its effectiveness in preventing galling and wear. In these experiments those materials that retained an effective film on the slider and disk and thus gave low friction-sliding time slopes were MoS_2, graphite (in moist air), zinc stearate, $CuBr_2$, $CoCl_2$, HgI_2, PbI_2, Ag_2SO_4, $CdCl_2$, AgI, and WS_2.

Type of structure can be a useful guide in the selection of low-shear-strength materials; low shear strength is considered of primary importance for obtaining solid lubricants with low friction coefficients. For example, materials of the $CdCl_2$, CdI_2, and other layer-lattice types generally show promise, and although they were not as effective as MoS_2, they were at least as effective as zinc stearate or graphite in these tests. An example of the inadequacy of type of structure as the guide is apparent when the results for the isomorphous compounds $AgSO_4$ and $NaSO_4$ are compared: $AgSO_4$ was an effective lubricant and $NaSO_4$ failed to lubricate.

The results with solid iodine as compared with CdI_2, HgI_2, and PbI_2 would indicate that the lubrication is a result of the structure rather than a decomposition of the solid with the liberation of free iodine which would be capable of reacting with the surface. However, partial decomposition and reaction may be a mechanism that holds the film to the surface of the metal. It has been suggested that reaction of sulfur from MoS_2 with metal is a factor in the adherence, although electron diffraction studies failed to indicate any reaction product between MoS_2 and steel (ref. 10).

The ability of a solid lubricant to form and maintain a continuous film is influenced by the materials being lubricated, the characteristics of the surface finish, the presence of other surface films, the environment of operation, the method of application, and several other less tangible factors. Use of solid lubricants such as those of this investigation must recognize these factors.

SUMMARY OF RESULTS

An experimental study of various solids as possible lubricants gave the following results:

1. Some solids with the $CdCl_2$, CdI_2, MoS_2, and other layer-lattice types provided effective lubrication. Those materials include CdI_2, $CdCl_2$, PbI_2, $CoCl_2$, $AgSO_4$, $CuBr_2$, and WS_2. They were not as effective as MoS_2 but were at least as effective as zinc stearate and graphite in these tests.

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2. Lubrication effectiveness could be attributed more to the formation of adherent films (either complete or partial) on the specimens rather than to any particular structural type. Silver iodide AgI, which does not have a layer-lattice structure, did provide effective lubrication because it formed an adherent lubricating film. Under conditions of low speed and high load used in these experiments, Fe_3O_4, mica, talc, and NiO were not adherent and did not provide effective surface protection.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 12, 1954

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TABLE I. - CRYSTAL TYPES[a] OF AX_2 COMPOUNDS

	Fluoride	Chloride	Bromide	Iodide	Hydroxide	Sulfide
Mg	CaF_2	$CdCl_2$	CdI_2	CdI_2	CdI_2	-------
Ca	CaF_2	--------	-------	CdI_2	CdI_2	-------
Ti	TiO_2	--------	-------	------	---------	CdI_2
Mn	TiO_2	$CdCl_2$	CdI_2	CdI_2	CdI_2	FeS_2
Fe	--------	$CdCl_2$	CdI_2	CdI_2	CdI_2	FeS_2
Co	--------	$CdCl_2$	CdI_2	CdI_2	CdI_2	FeS_2
Ni	--------	$CdCl_2$	$CdCl_2$	$CdCl_2$	$CdCl_2$	FeS_2
Zn	TiO_2	$CdCl_2$	CdI_2	CdI_2	CdI_2	-------
Sr	CaF_2	CaF_2	-------	------	---------	-------
Mo	--------	--------	-------	------	---------	MoS_2
Pd	--------	$CdCl_2$	-------	------	---------	CdI_2
Co	--------	$CdCl_2$	$CdCl_2$	CdI_2	CdI_2	CdI_2
Sn	--------	--------	-------	------	---------	CdI_2
Ba	CaF_2	--------	-------	------	CdI_2	-------
W	--------	--------	-------	------	---------	MoS_2
Pt	--------	$CdCl_2$	-------	------	---------	CdI_2
Hg	--------	$HgCl_2$	$HgBr_2$	$HgBr_2$	---------	-------
Pb	--------	$PbBr_2$	$PbBr_2$	CdI_2	---------	CdI_2

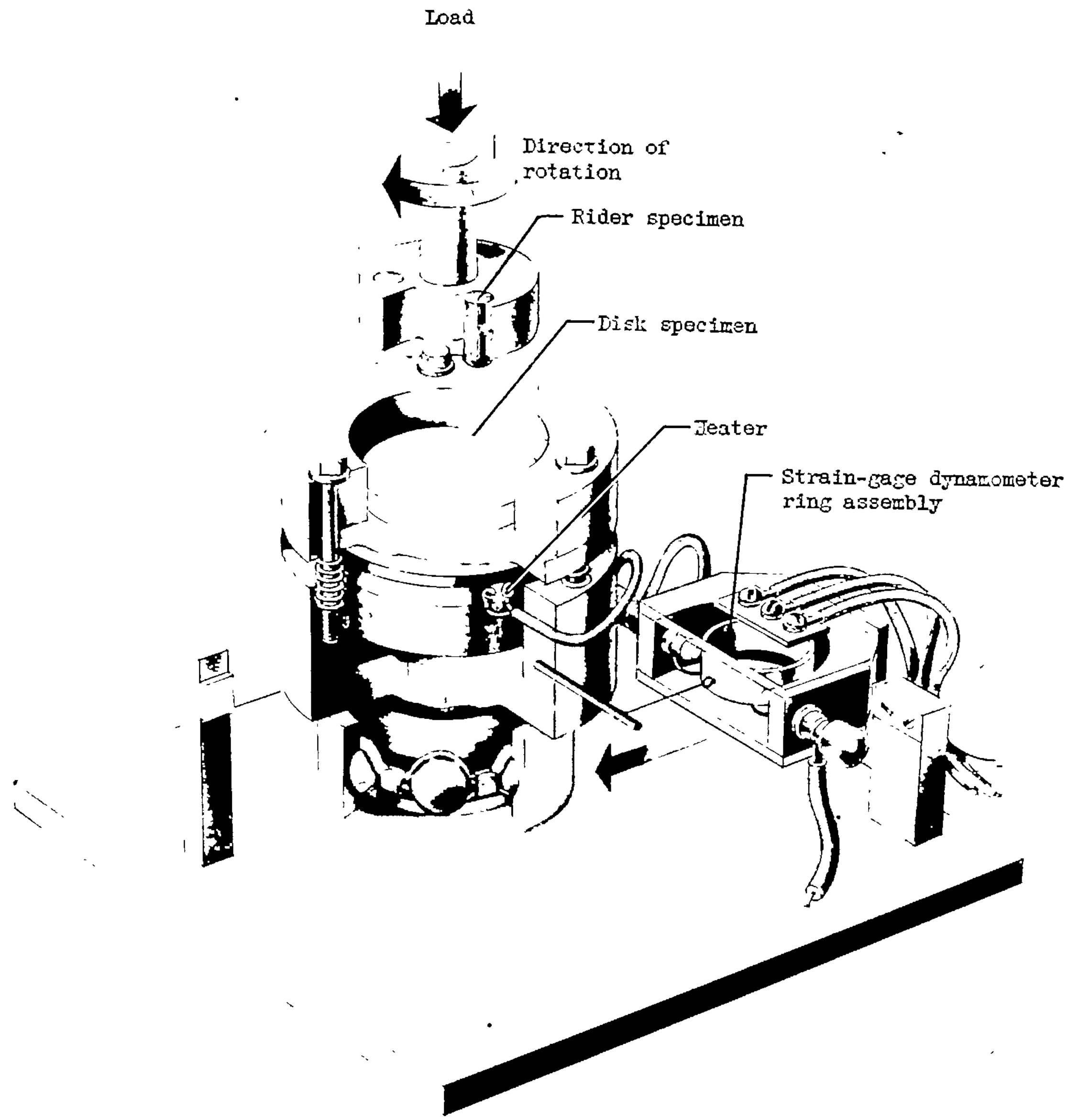
[a]Ref. 2.

TABLE II. - SOLIDS USED

Material	Purity	Affinity for water (a)	Coefficient of friction		Wear area, sq in.	Observed effect of solid on specimens
			(1 min sliding)	(30 min sliding)		
Effective lubricants						
MoS_2	Possibly slight oxide present	Insoluble	0.017	0.047	0.0016	None
CdI_2	Chemically pure	Soluble	.04	.06	.0023	None
$CdCl_2$	Chemically pure	Soluble	.03	.07	.0019	None
WS_2	Unknown	Insoluble	.05	.08	.0018	None
Ag_2SO_4	Chemically pure	Slightly soluble	.14	.14	Negligible	None
PbI_2	Chemically pure	Slightly soluble	.28	.28	.0018	None
Graphite	Purified commercial lubricant small particle size	Absorbs water	.06	.11	.0034	None
$Zn(C_{18}H_{35}O_2)_2$	Chemically pure	Insoluble	.07	.11	.0032	None
$CoCl_2$	Prepared by dehydration	Soluble	.04	.10	.0020	Slight rusting
HgI_2	Chemically pure	Very slightly soluble	.18	.18	.0021	Appreciable corrosion
$CuBr_2$	- - - - - - - -	Deliquescent	.04	.06	.0021	Considerable rusting
AgI	Chemically pure	Insoluble	.19	.25	.0033	None
SAE 60	- - - - - - - -	- - - - -	.13	.108	.0020	- - - - - - -
Ineffective lubricants						
$NiCl_2$	Prepared by dehydration	Deliquescent	0.03	0.10-.15	0.0024	Rusting
$Ca(OH)_2$	Chemically pure	Slightly soluble	.18	.2 -.25	.0026	None
$Mo(OH)_2$	Chemically pure	Soluble	.32	(b)	- - -	None
TiS_2	Unknown	Hydrolysis	.20	(b)	- - -	- - - - - - -
I_2	- - - - - - - -	- - - - -	.15	.30	- - -	- - - - - - -
$HgCl_2$	Chemically pure	Soluble	.32	.38	- - -	Appreciable corrosion
$PbCl_2$	Chemically pure	Slightly soluble	.31	.45	.0029	None
AgCN	Unknown	Insoluble	.02	- -	.0036	- - - - - - -
CuCl	Chemically pure	Slightly soluble	.38	.37	.0039	Slight rusting
Na_2SO_4	Chemically pure	Soluble	.36	(b)	- - -	None
Fe_3O_4	Chemically pure	Insoluble	(b)	- -	- - -	None
BN	Technical grade	Insoluble	(b)	- -	- - -	None
NiO	Chemically pure	Insoluble	(b)	- -	- - -	None
Mica	Technical grade	Insoluble	(b)	- -	- - -	None
Talc	Unknown	Insoluble	(b)	- -	- - -	None

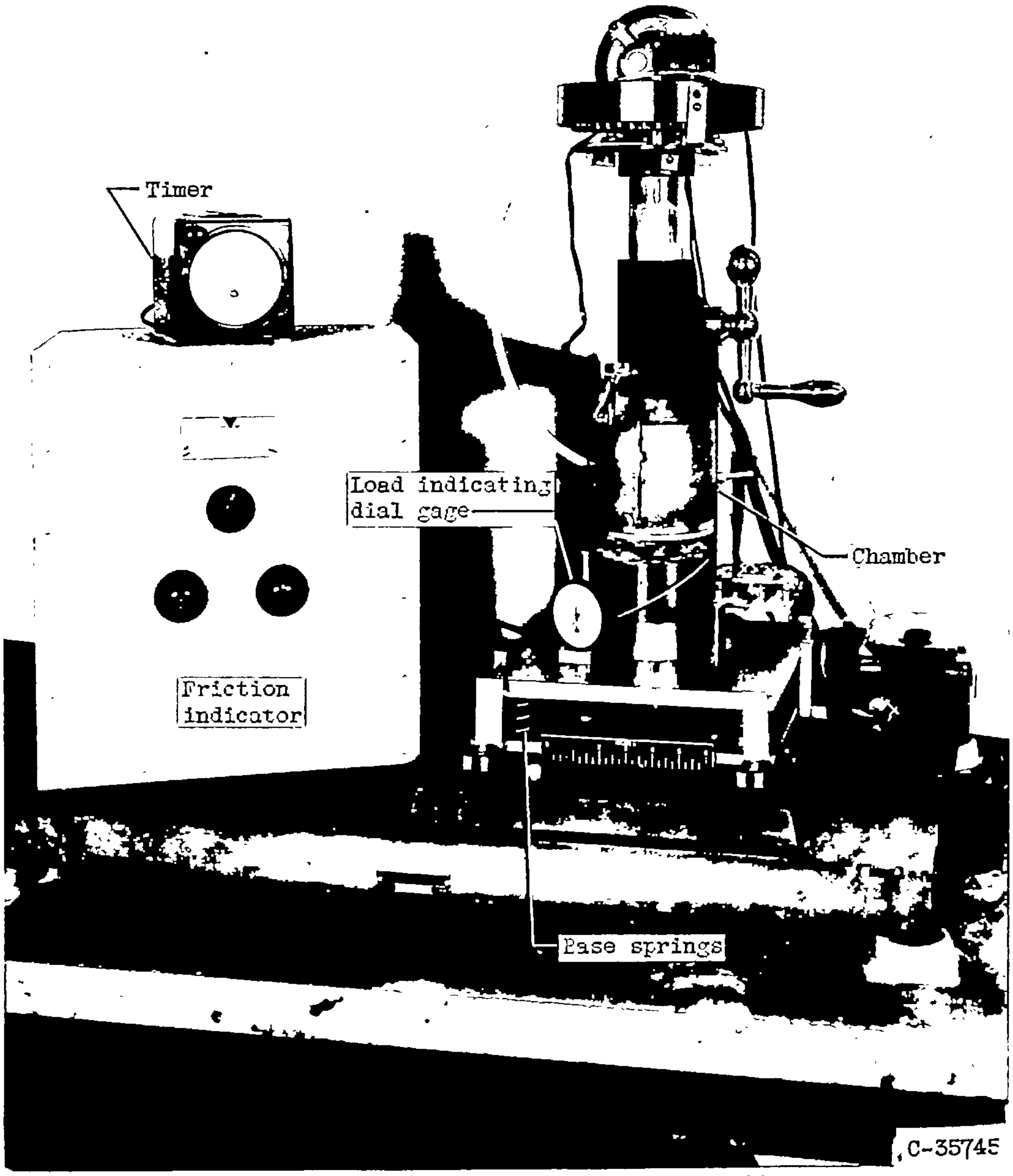
[a]Ref. 11.

[b]Failed to lubricate.



(a) Diagrammatic sketch.

Figure 1. - Friction apparatus.



(b) General view.

Figure 1. - Concluded. Friction apparatus.

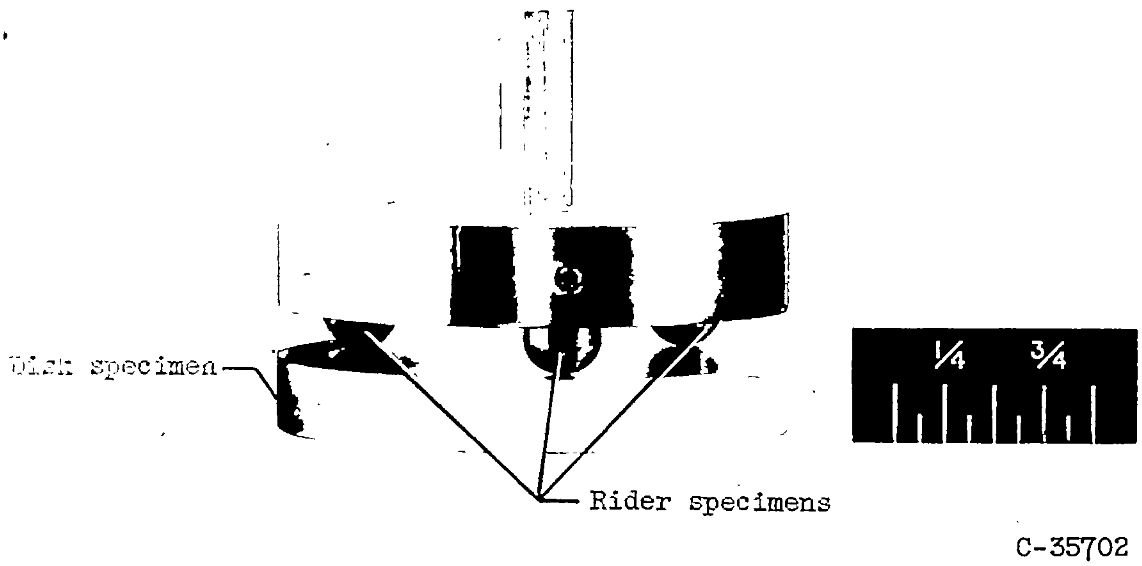


Figure 2. - Friction specimens.

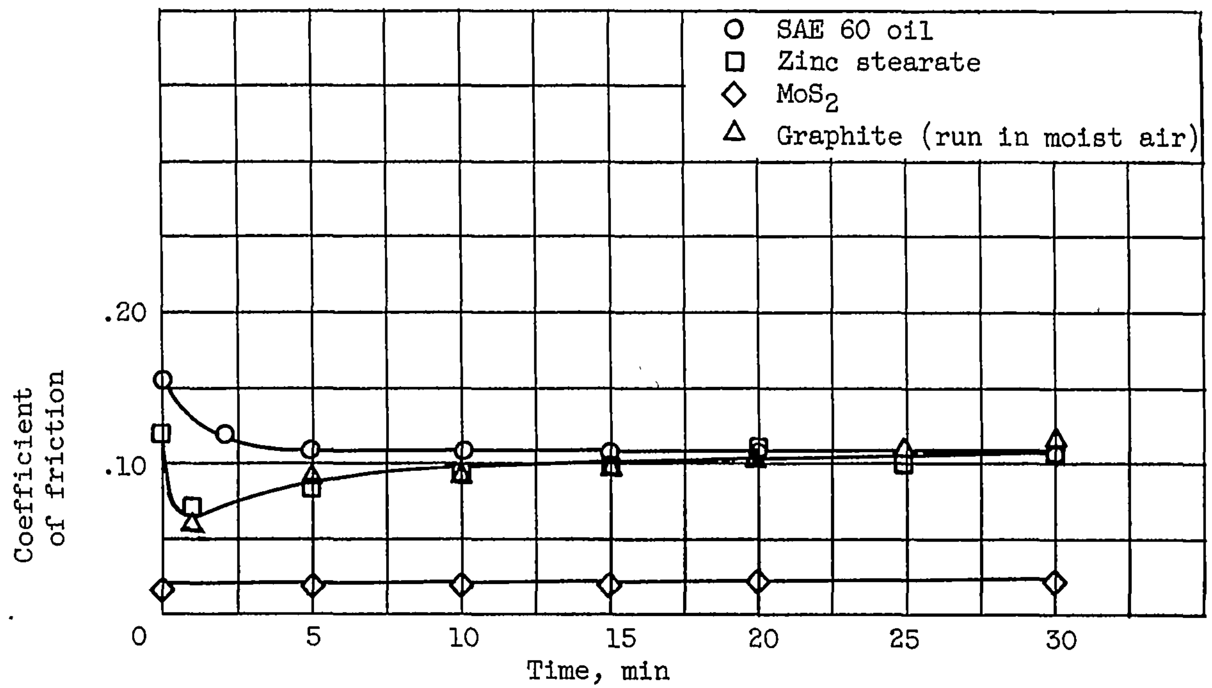
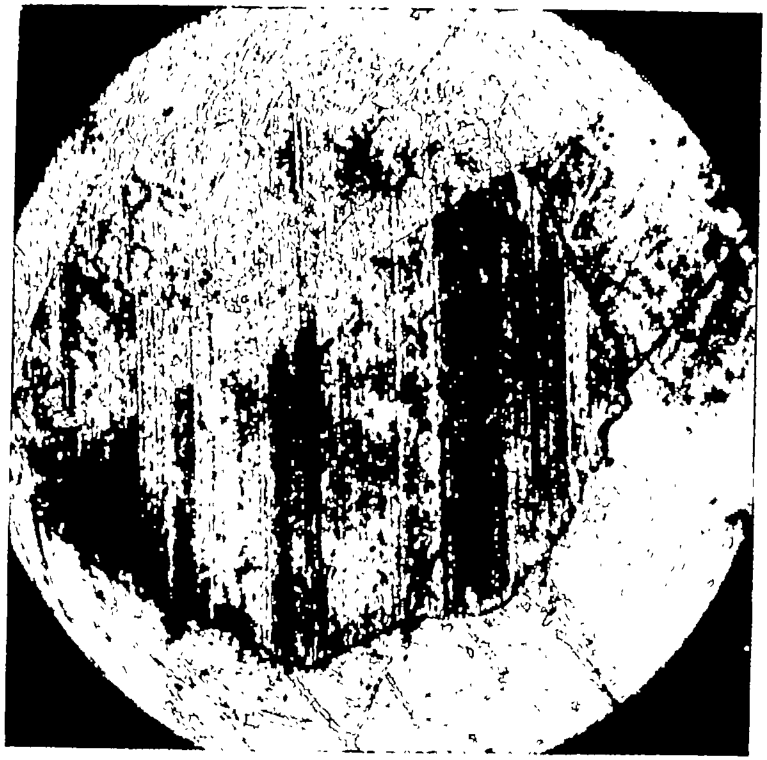
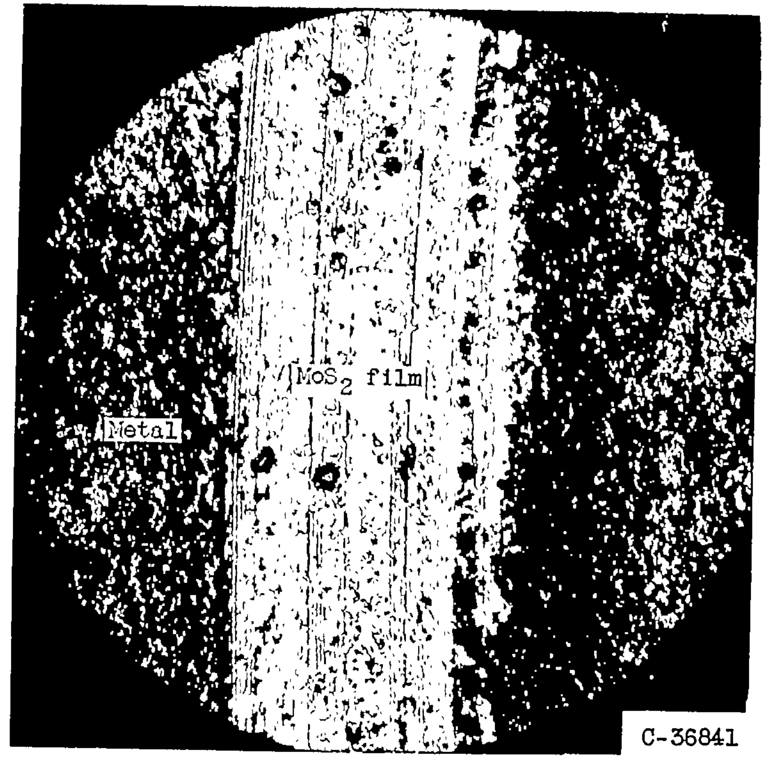


Figure 3. - Effect of sliding time on coefficient of friction for steel against steel using various materials as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.



(a) Slider; X100.



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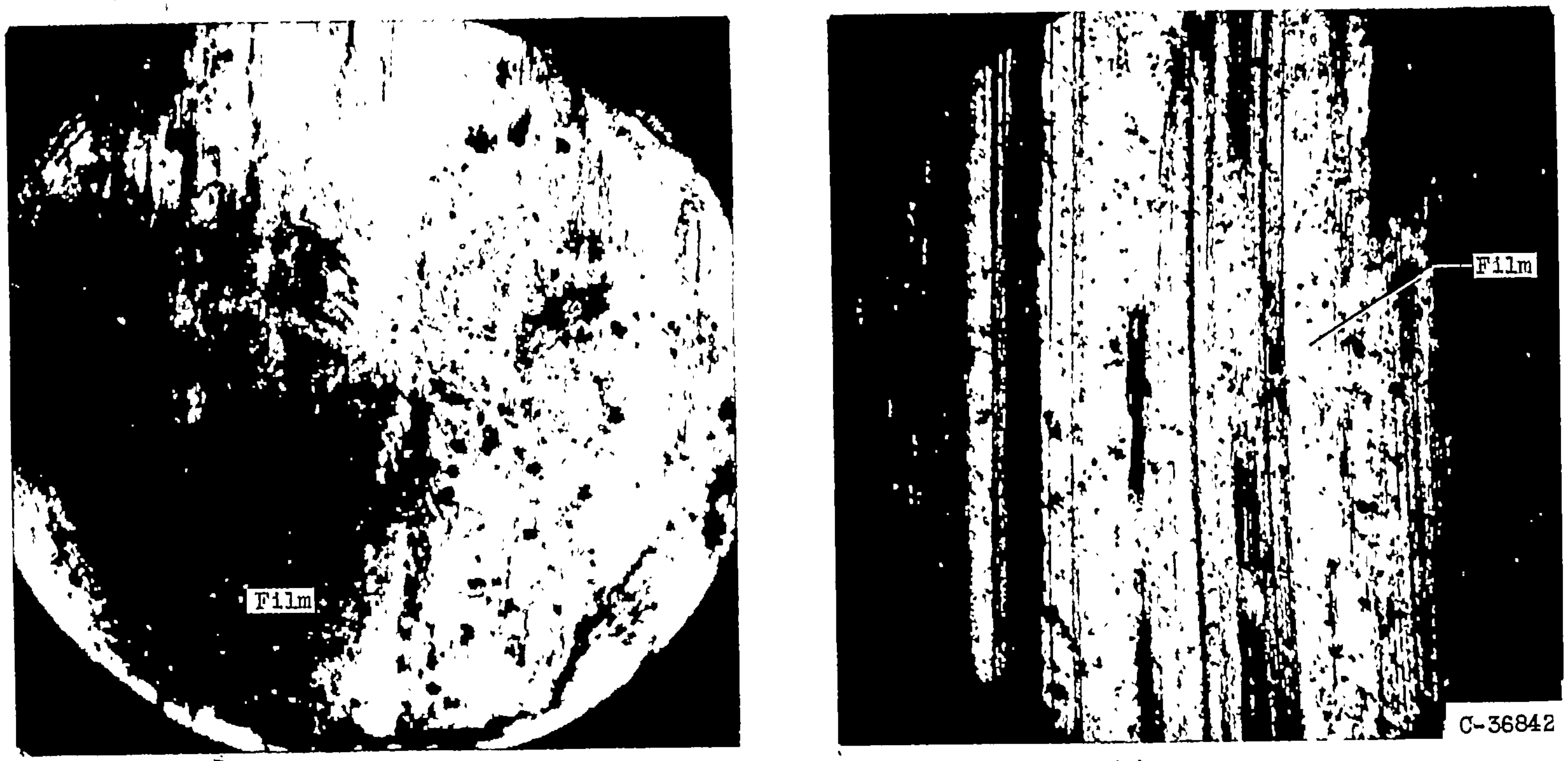
(b) Disk; X50.

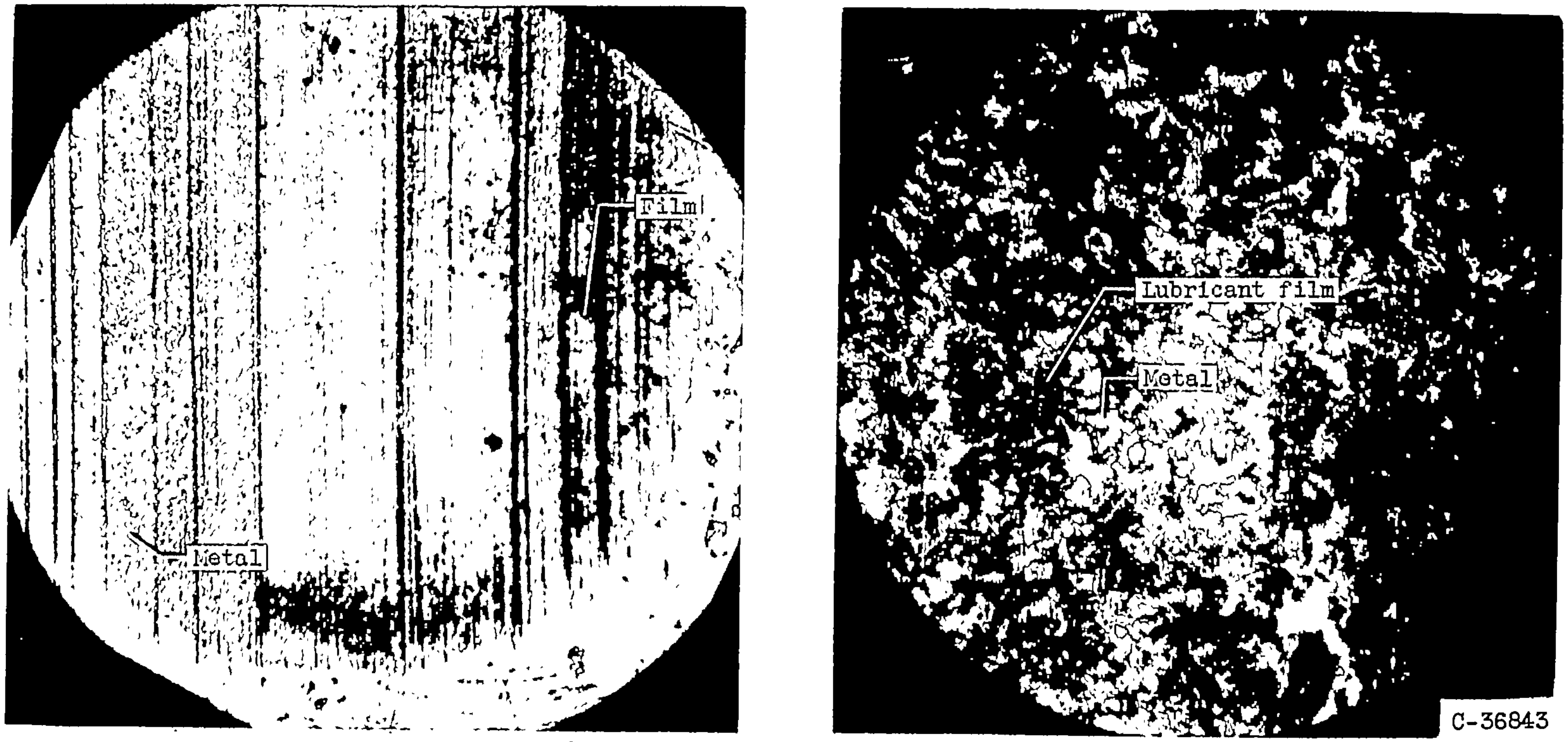
Figure 4. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant MoS_2. A continuous film is formed on both slider and disk.



(a) Slider; X100.

(b) Disk; X50.

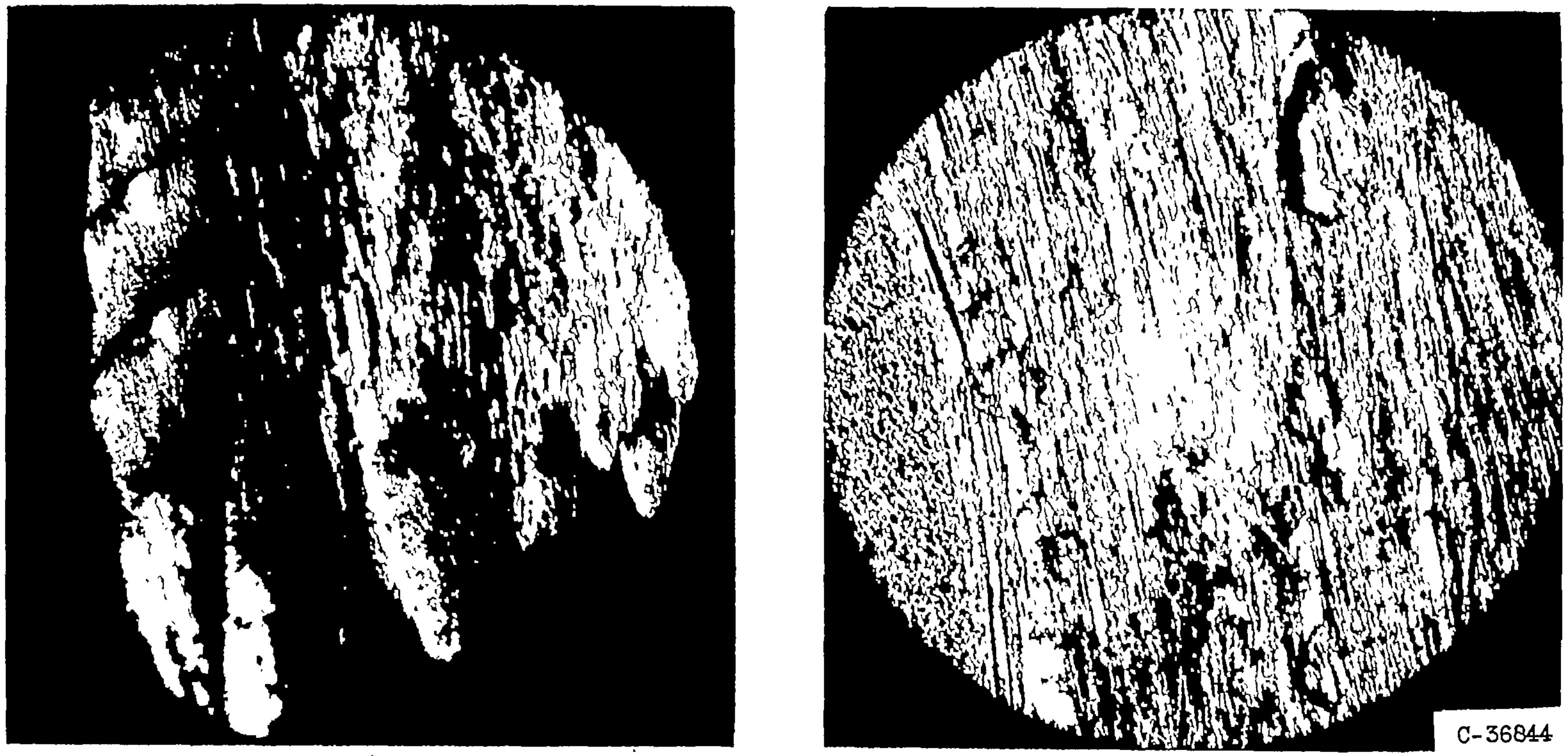
Figure 5. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant graphite. A film is formed on both slider and disk.



(a) Slider; X100.

(b) Disk; X50.

Figure 6. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant zinc stearate. Thin film is formed on slider; on disk, metal is visible through film.



(a) Slider; X50.

(b) Disk; X50.

Figure 7. - Photomicrographs of surfaces after 1-minute sliding time with solid lubricant Fe_3O_4. No surface protection occured under these conditions.

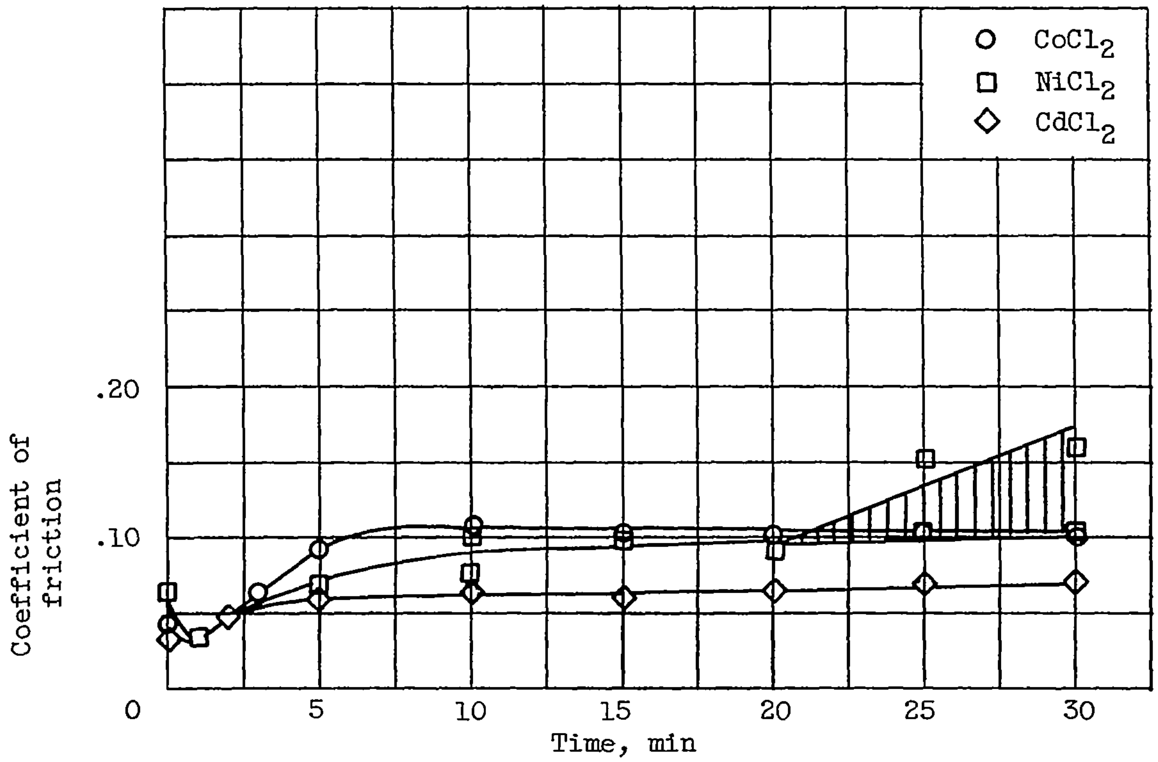
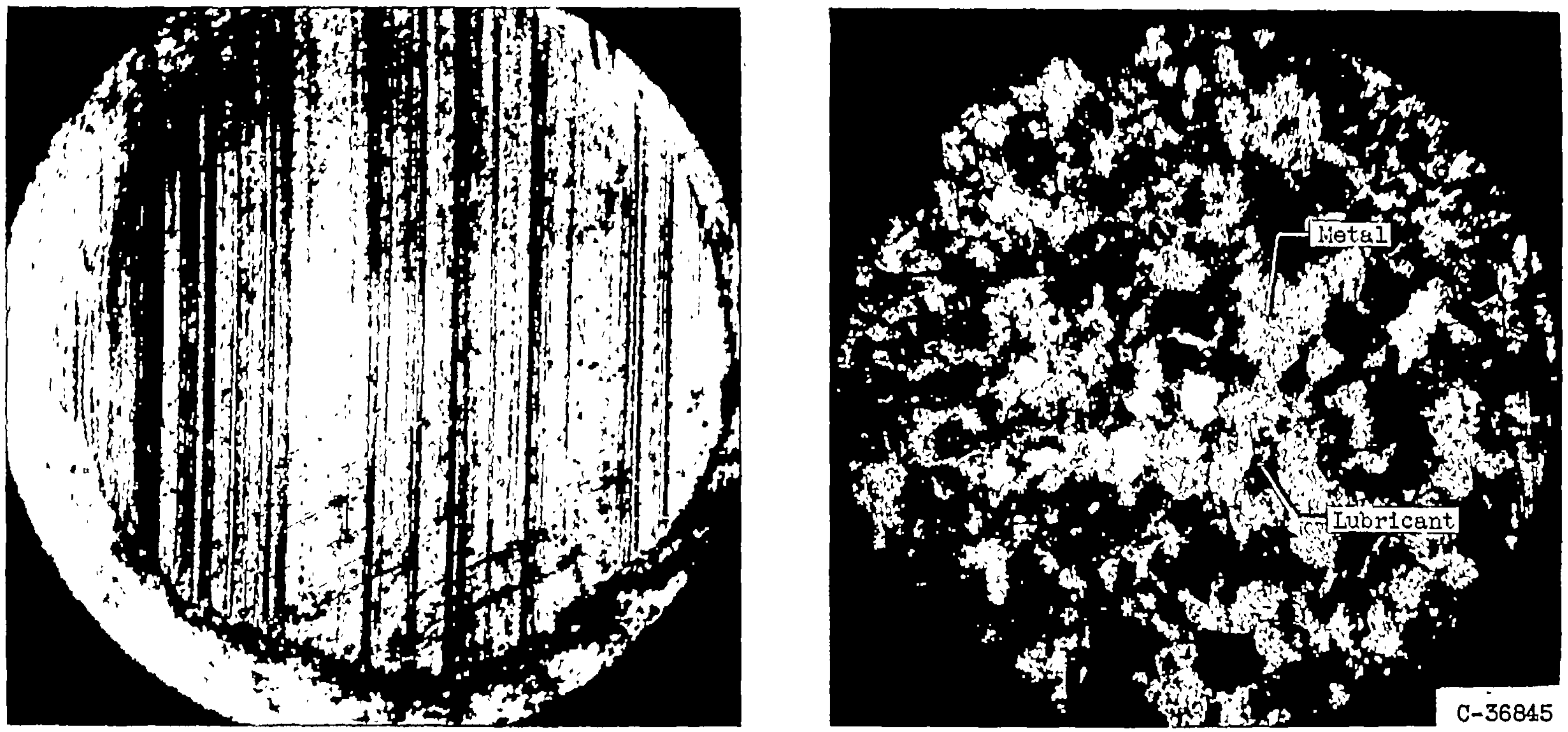


Figure 8. - Effect of sliding time on coefficient of friction for steel against steel using various solids with $CdCl_2$ structure as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.



(a) Slider; X100.

(b) Disk; X100.

Figure 9. - Photographs of surfaces after 30-minute sliding time with solid lubricant $CoCl_2$. No film formed on slider; on disk, metal is visible through a continuous film.

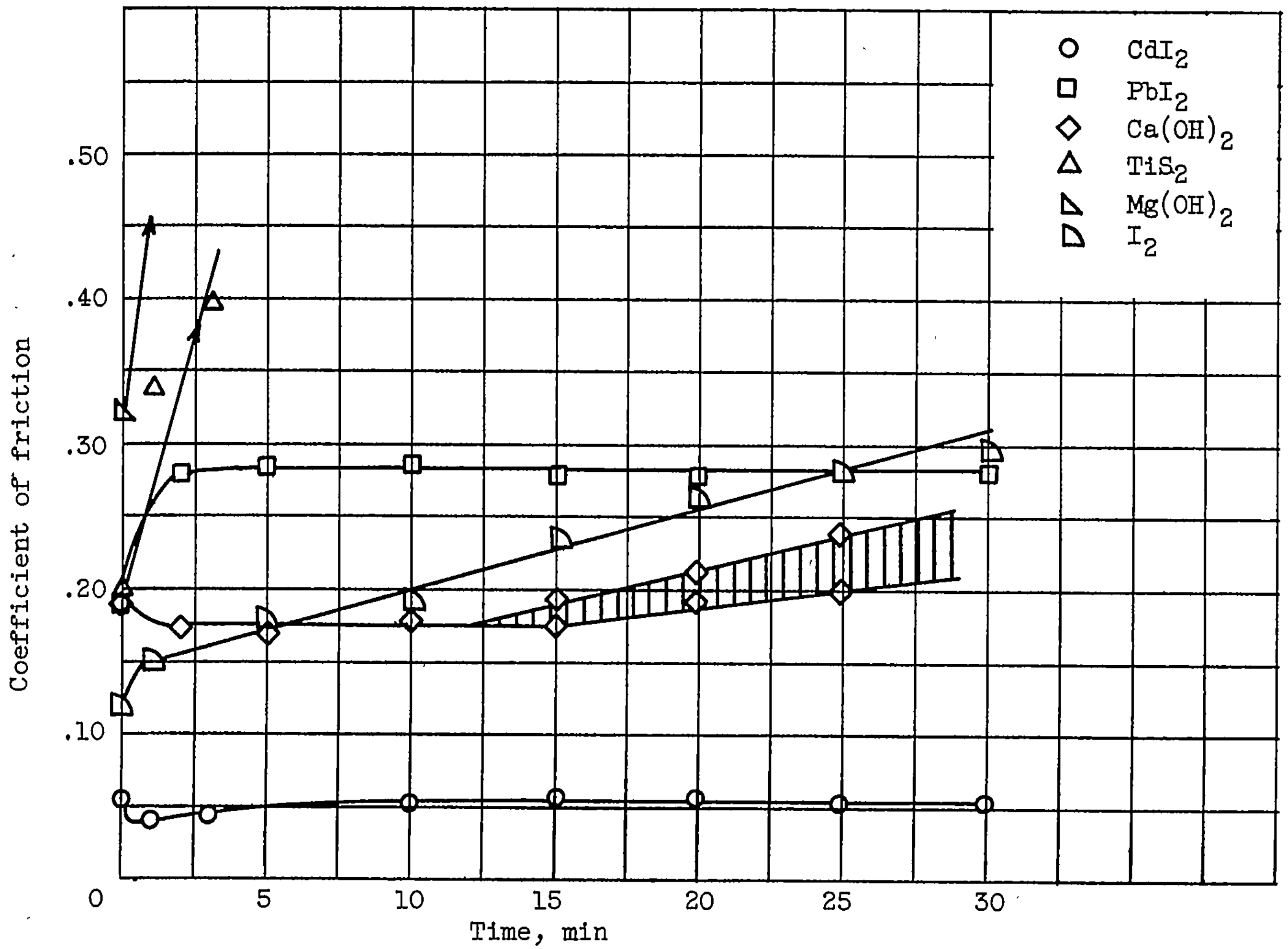
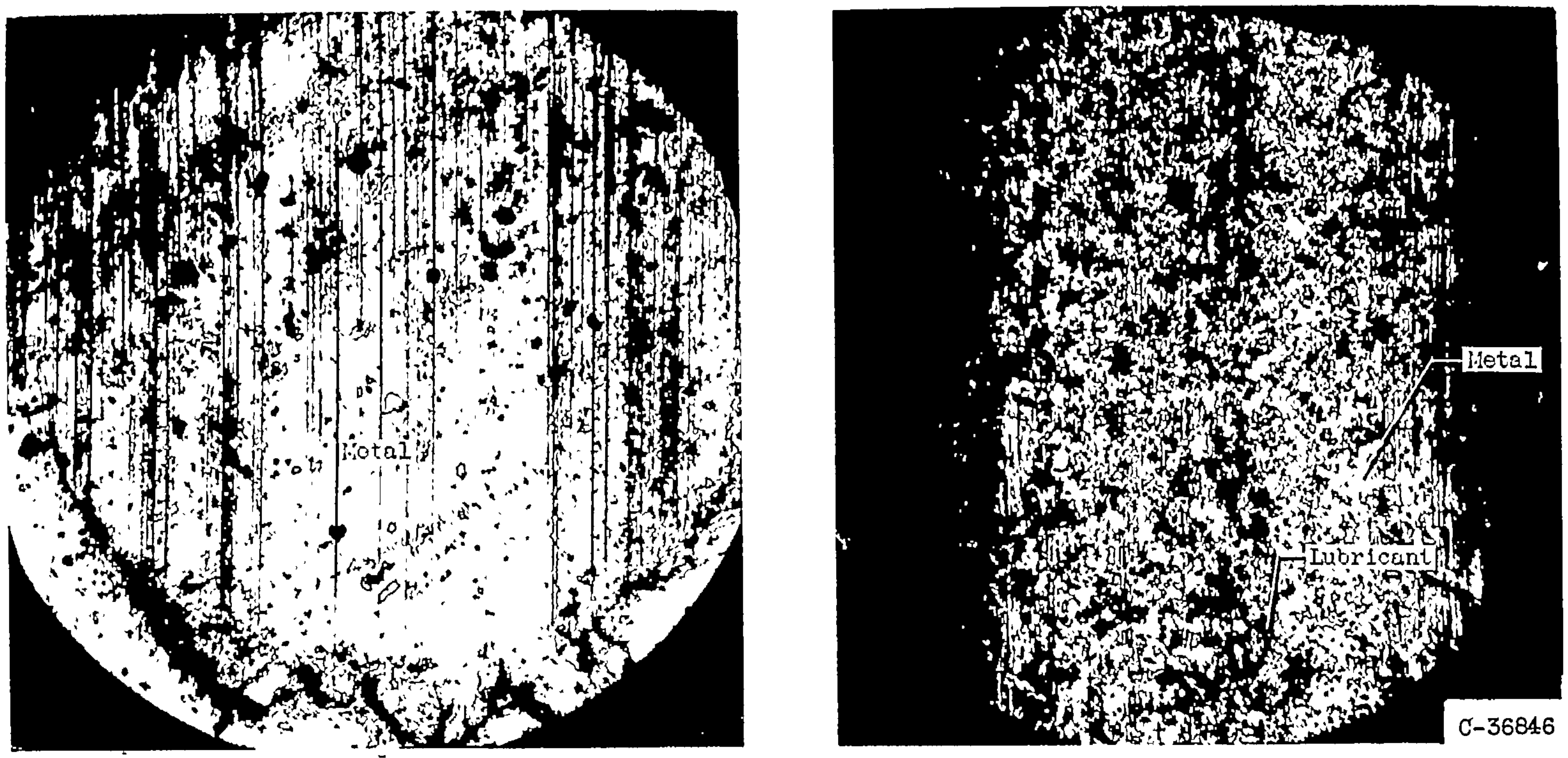
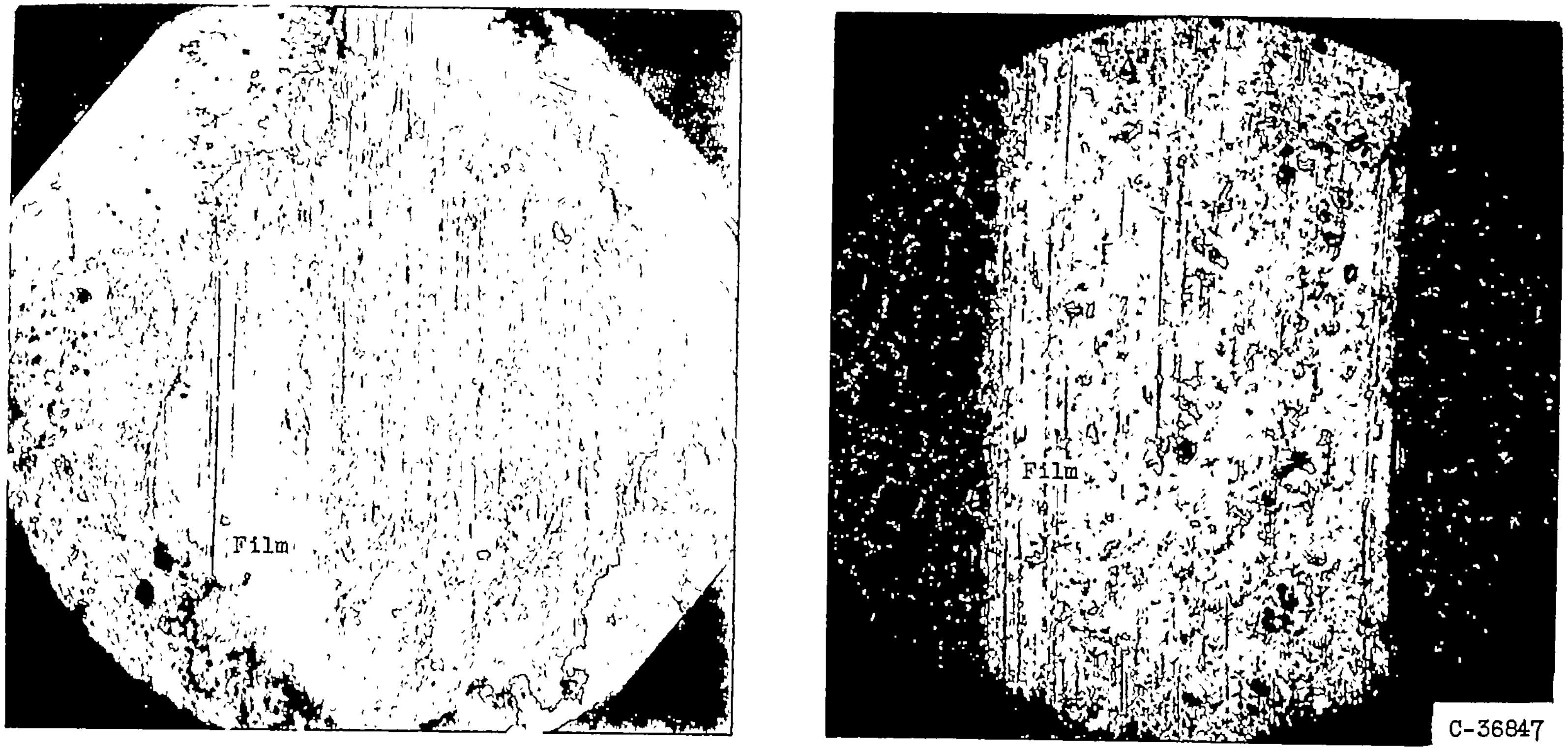


Figure 10. - Effect of sliding time on coefficient of friction for steel against steel using various solids with CdI_2 structure as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.



(a) Slider; X100. (b) Disk; X50.

Figure 11. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant $Ca(OH)_2$. No apparant film on slider and much metal visible through film on disk.



(a) Slider; X100.

(b) Disk; X50.

Figure 12. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant PbI_2. Thick film formed on both slider and disk.

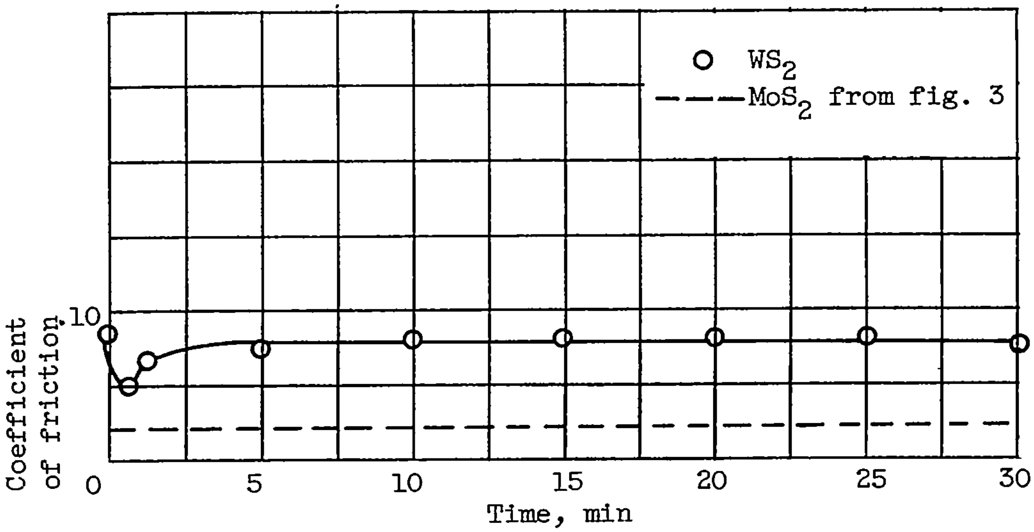


Figure 13. - Effect of sliding time on coefficient of friction for steel against steel using various solids with MoS_2 structure as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.

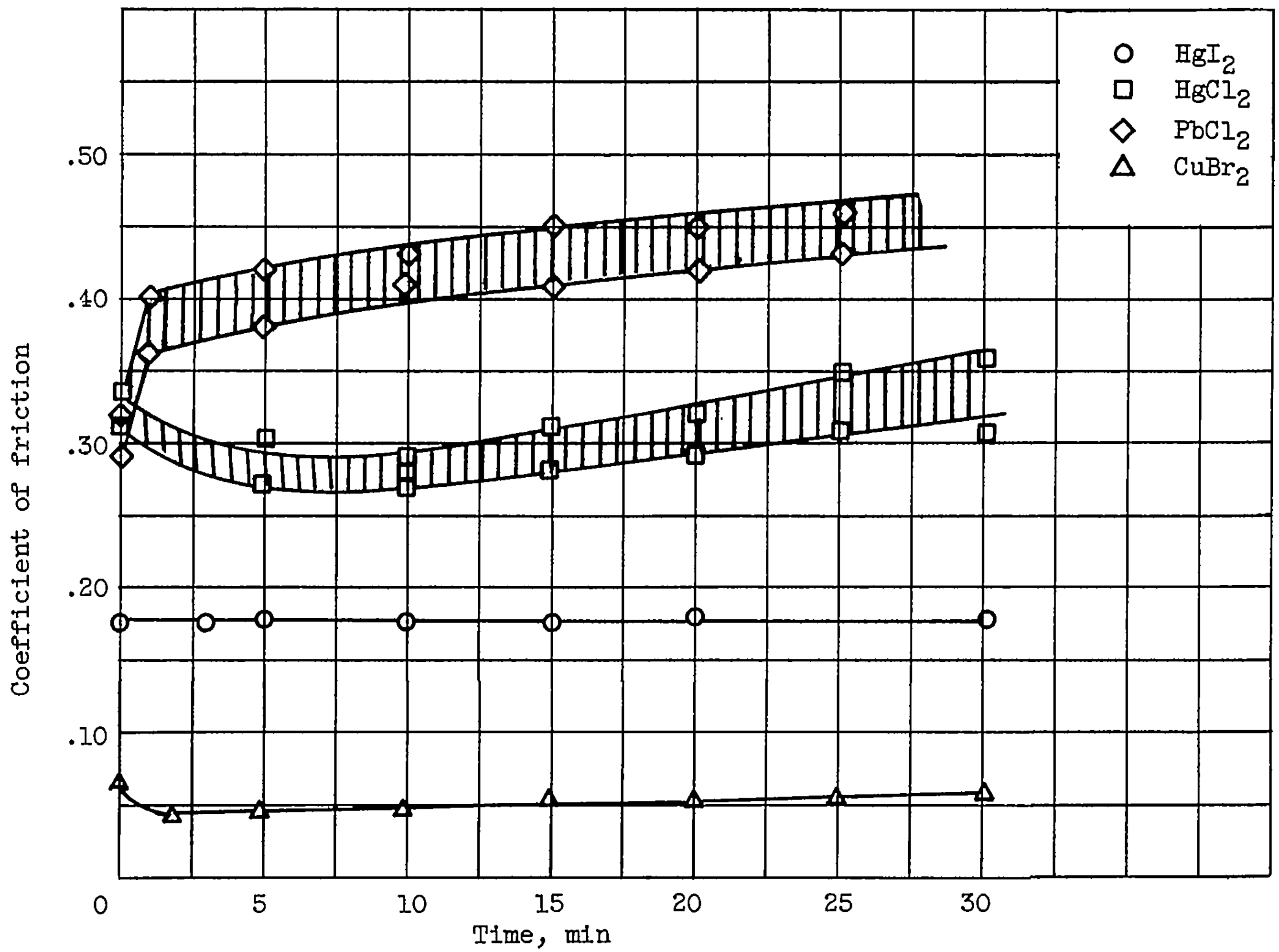


Figure 14. - Effect of sliding time on coefficient of friction for steel against steel using various solids with transition lattices as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.

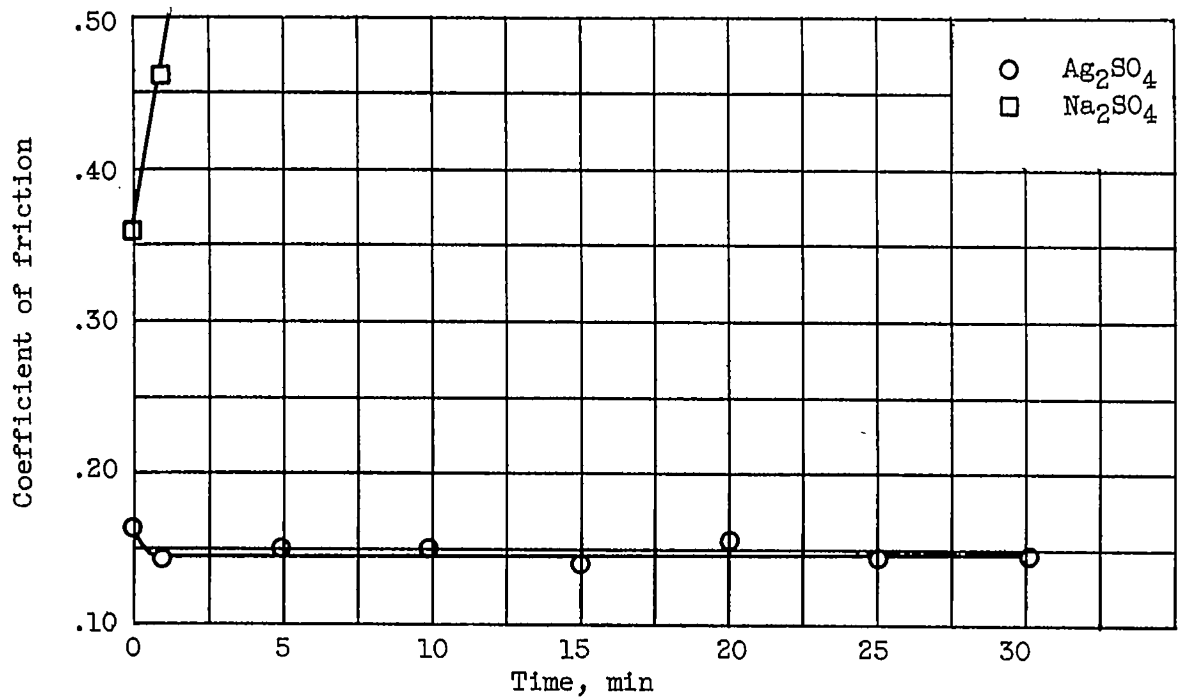
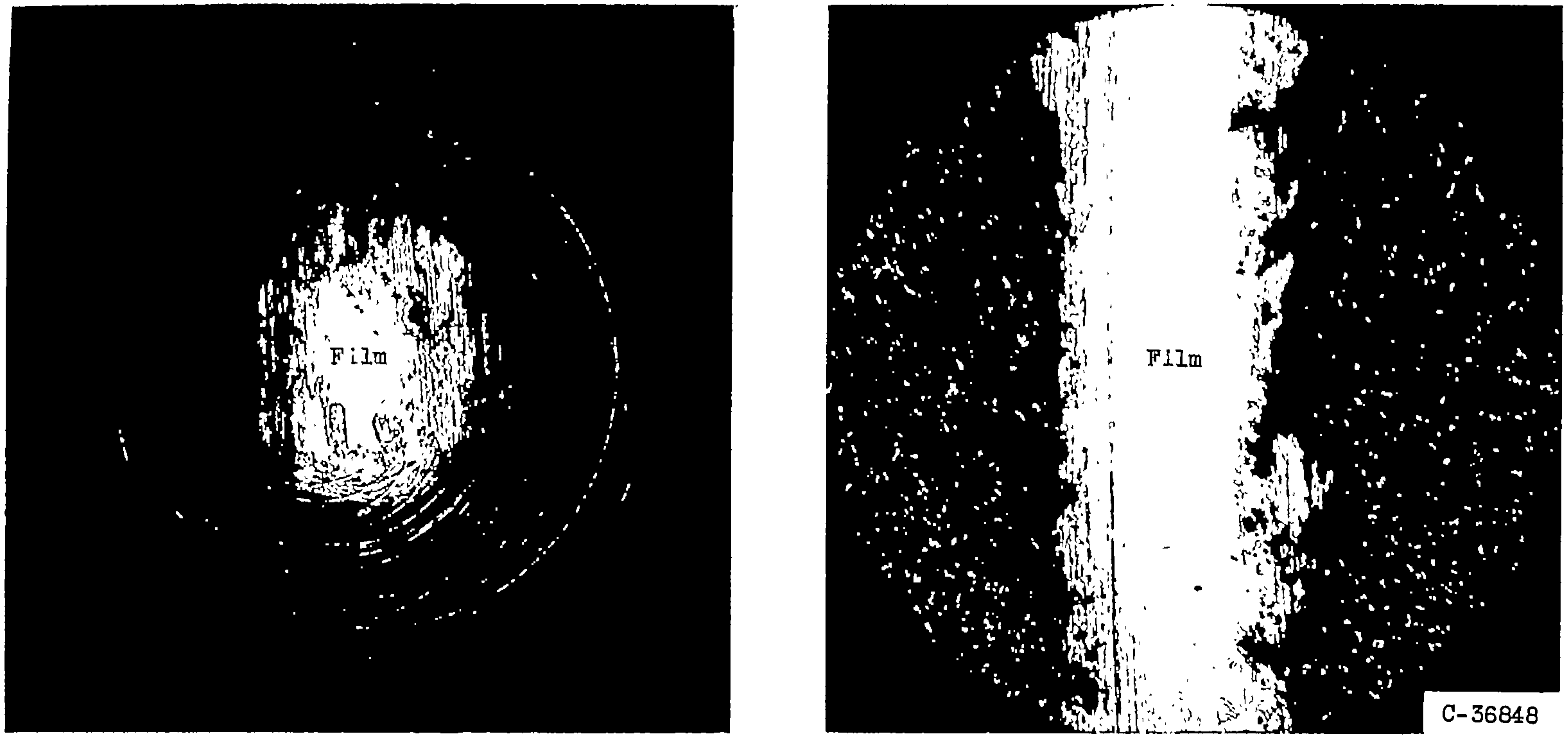
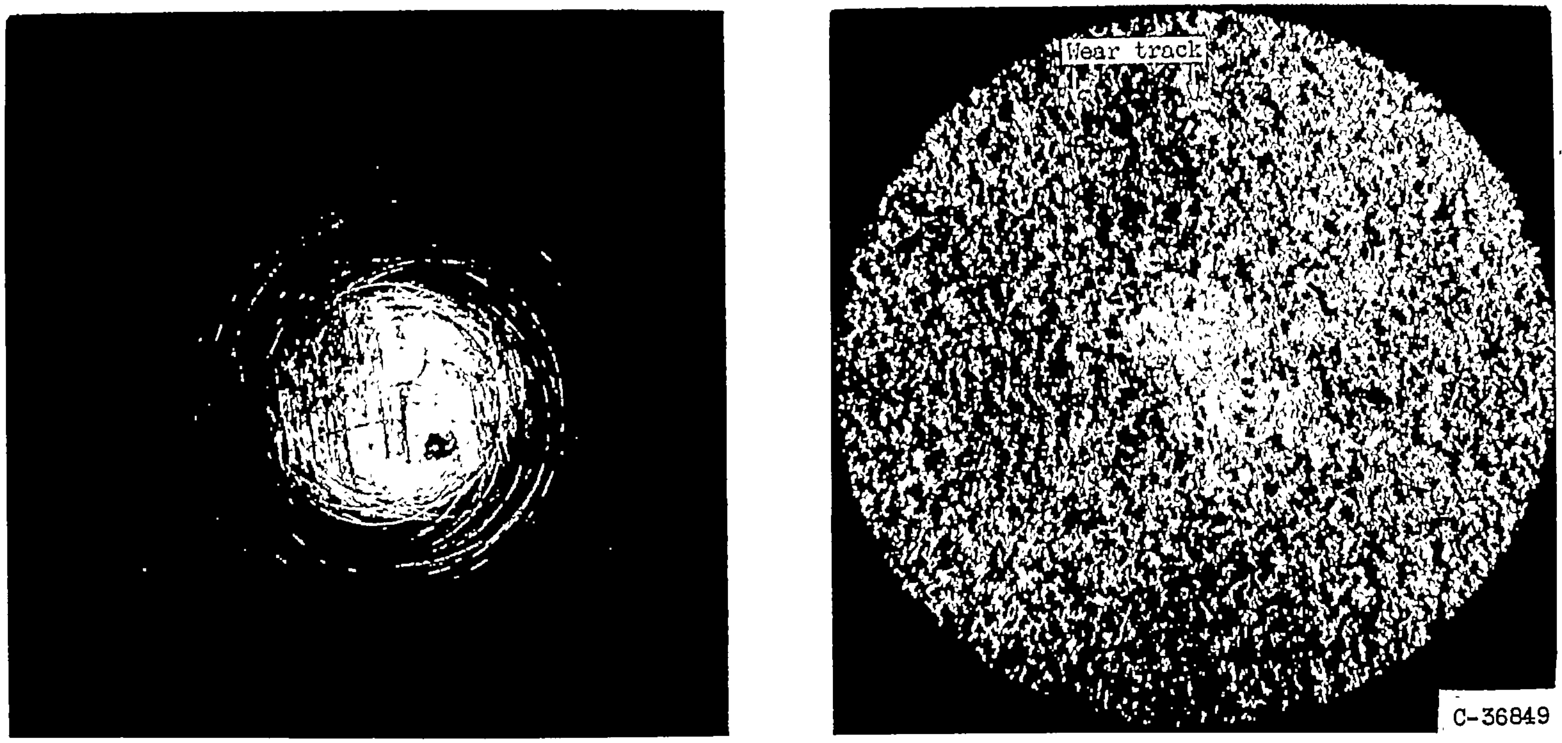


Figure 15. - Effect of sliding time on coefficient of friction for steel against steel using various solids with Na_2SO_4 structure as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.



(a) Slider. (b) Disk.

Figure 16. - Photomicrographs of surfaces after 30-minute sliding time showing surface protection afforded with solid lubricant Ag_2SO_4. X50.



(c) Slider with film dissolved away.

(d) Disk with continuous film dissolved away.

Figure 16. - Continued. Photomicrographs of surfaces after 30-minute sliding time showing surface protection afforded with solid lubricant Ag_2SO_4. X50.

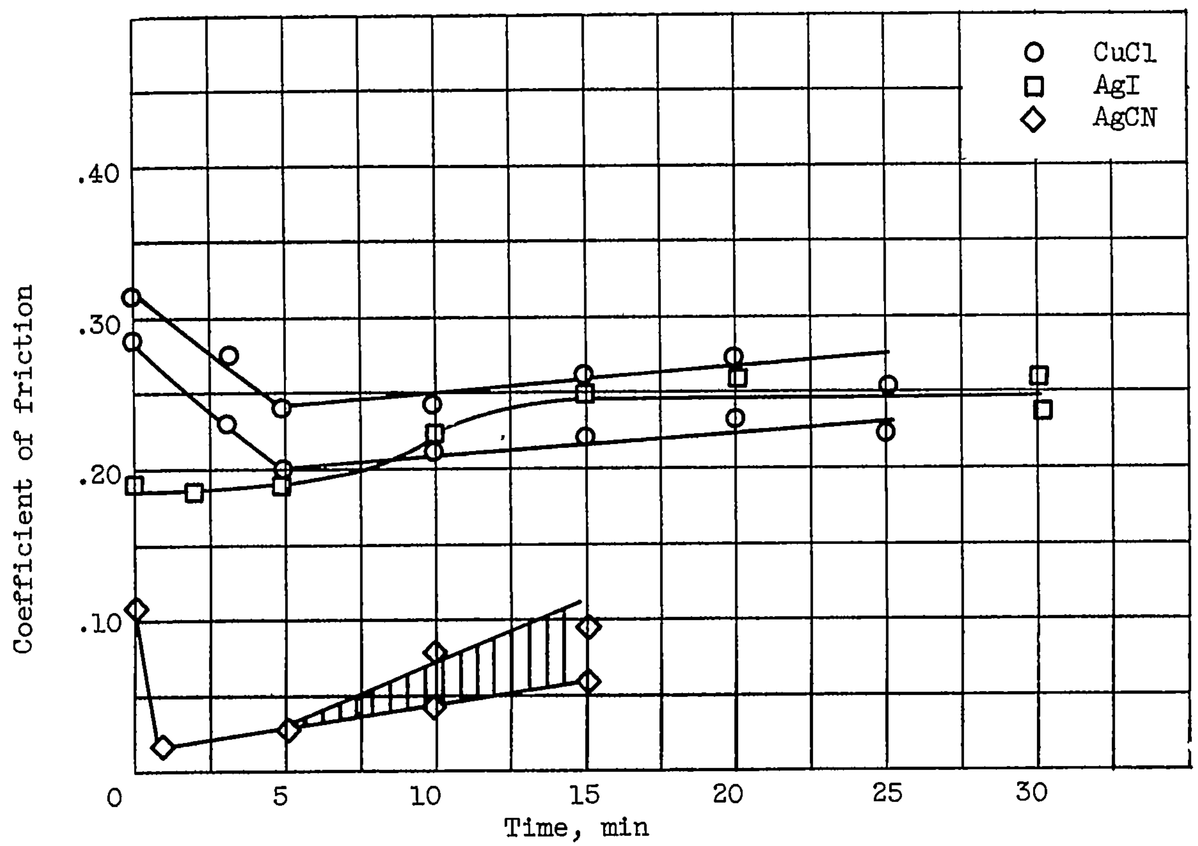
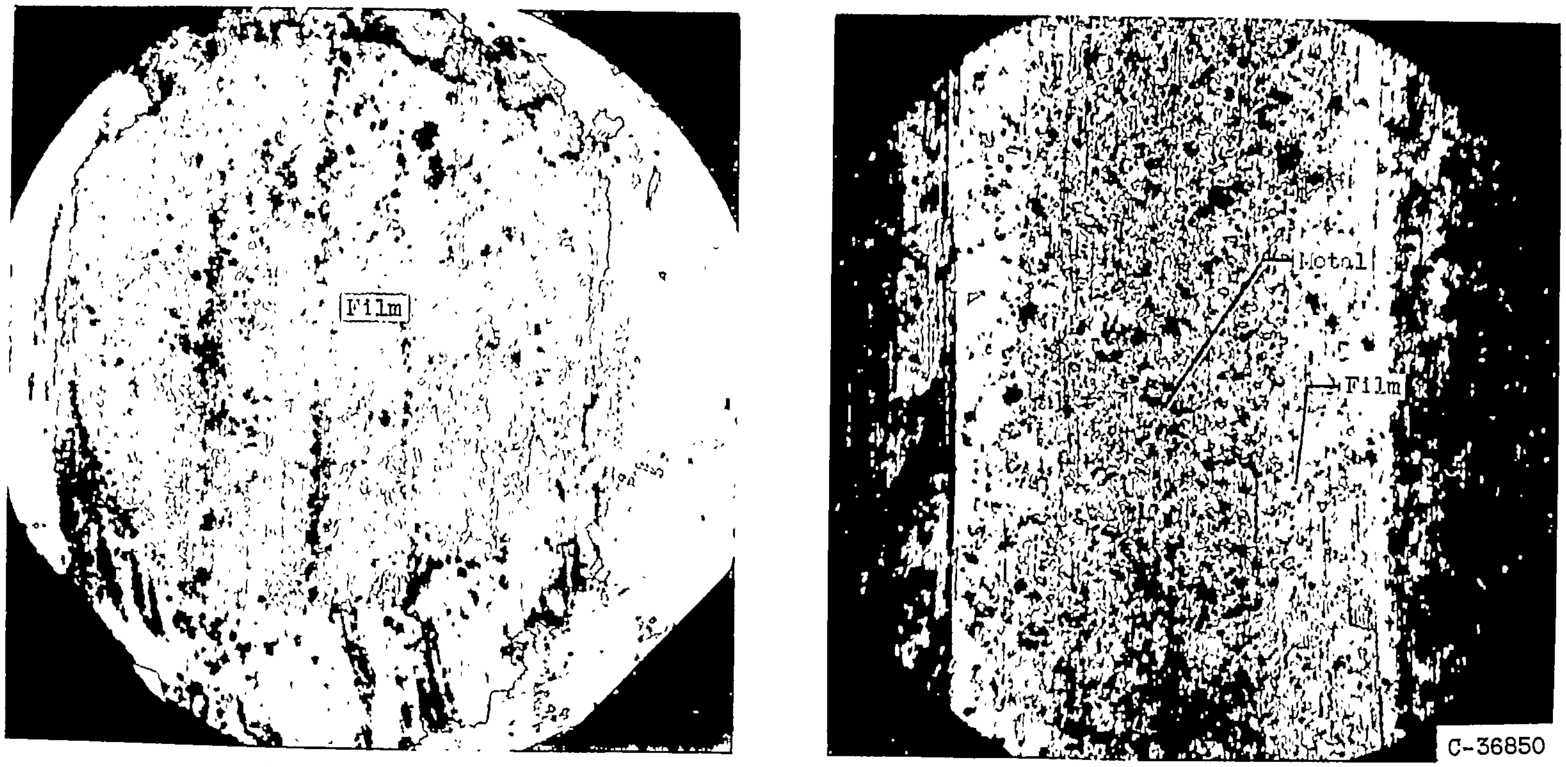


Figure 17. - Effect of sliding time on coefficient of friction for steel against steel using solids with low shear strength as lubricants. Sliding velocity, 5.7 feet per minute; load, 40 pounds; atmosphere, dry air.



(a) Slider; X100.

(b) Disk; X50.

Figure 18. - Photomicrographs of surfaces after 30-minute sliding time with solid lubricant AgI. Film formed on slider and on disk; much metal visible through disk film.

NACA - Langley Field, Va.